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External costs of fossil electricity generation: Health-based assessment in Thailand

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ABSTRACT

Airborne pollutants from fossil fuel burning in electricity generation potentially contribute a number of consequent environmental impacts. In order to indicate the actual costs of energy, a so-called external cost has become of growing concerns internationally. This study aims to evaluate the external costs related to human health degradation resulting from Thai electricity generation produced from fossil fuel which operated during the period from 2006 to 2008. Impact Pathway Approach (IPA) was applied in the analysis. The advections of the criteria pollutants (SO_2, NO_X, and PM_{10}) including secondary particulates (sulfate and nitrate aerosols) had been simulated using the CALMET/CALPUFF modeling system. Subsequently, the exposure-response functions (ERFs) were used to quantify the marginal damage to public health. Finally, costs of such damages were then estimated based on welfare economics. The results showed that the criteria pollutants caused significant damage to both premature mortality and morbidity. The average damage cost was totally about 600 million 2005 US$ annually which ranged between 0.05 and 4.17 US$ cent kWh^{-1} depending on fuel types. It implies that the external costs are significant to the determination of electricity market price. With the damage costs being included, the electricity price will reflect the true costs of the generation which will be beneficial to the society as a whole.

Contents

1. Introduction

Energy use and its adverse impacts on environmental problems have become a major issue in the last few decades. Countries around the world are facing experience of increasing environmental problems resulting from rapid growth of energy consumption. Fossil energy has been demonstrated to be the most important cause of environmental damages to wide range of receptors both in local and global levels. However, fossil fuel remains the dominant sources of primary energy especially in developing countries [1] and still seems to be the most competitive energy according to current technologies. A number of studies obviously indicate that such impacts can be potentially damage to human health, crops, building materials, ecosystems, climate, etc. [2]. These impacts are mostly externalities which are not traditionally reflected or

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included in the determination of energy market price. This has led to numerous studies to quantify a so-called external cost in order to take the externalities into account for policy making. Internalizing the external cost into energy production cost is a useful measure to indicate the actual costs of energy. The result can be applied to enforcement of pollutant fees, subsidization of alternative energy, and promotion of newer and cleaner technologies [3,4]. As a consequence, other cleaner fuel prices become relatively more competitive on commercial energy market.

Electricity generation is also one of the major sources of environmental problems. Air pollution of fossil fuel combustion process contributes a number of consequent impacts with the most significance appearing to be the damage to human health. As above mentioned, there are a number of studies attempting to quantify the external cost of electricity. Nevertheless most methodologies used for those studies were generally initiated with environment and background of developed countries and are also likely applicable for developed countries. Due to a large amount of information required in the analyses, the application of these methods is considerably limited for most developing countries. In order to apply the approach, some of unavailable or incomplete data may, however, be transferred from that of developed countries [5].

Generally, two main methods used to study on externalities of electricity generation are top-down and bottom-up approach [6]. The top-down approach is normally based on highly aggregated damages and emissions in national or regional level which is usually applied in most of former studies. The results of this approach provide overall average figures which do not include site-specific information. The recent prominent bottom-up approach is the impact pathway approach (IPA) implemented in the ExternE project [2]. The approach introduces a methodology of evaluating externalities in a logical manner. The first stage begins with quantifying the pollutant emissions from considered sources, and then dispersion model is used to pursue the analyzed pollutants within studied domain. The marginal damages resulting of the pollutants are appraised by dose–response functions. Finally, the damages are then estimated in monetary value [6,7].

This study was to evaluate the external costs of electricity generation in Thailand. Most of existing fossil fuel-fired power plants had been selected. The period of the study was between 2006 and 2008. The marginal damages were considered within territorial boundary of Thailand. It should be emphasized that this work focused on local externalities which related to national human health impacts. The carbon dioxide (CO_2) emission which is primary cause of global-level problems was beyond the scope of this study. In the analysis, the IPA was applied. In order to define the appropriate national values, an extensive review of the related information from available published papers in Thailand was conducted, together with other country-based data.

2. Airborne emission of Thai fossil power plants

In Thailand, there has been realization of public burden resulting from air pollution. The national ambient air quality standard (NAAQS) has been firstly promulgated since 1981 with subsequent adjustments in 1992. The standards were considered on the basis of public health criteria related to threshold level of pollutants concentration and time of exposure. The values were set for the average concentration of certain duration of time e.g. 1 h, 24 h, or 1 year. The standard for short time of exposure was developed to prevent acute effects while longer exposure time was used to prevent chronic effects. Moreover, limiting values of emitted pollutants from power plants have been also proclaimed. However the values assigned to the new expansions differed from existing old plants (installed before 1996).

The electricity generation capacity in the country has been projected to increase from 29,212 MW in the early 2010 to 65,547 MW in 2030 in order to adequately serve more than double of electricity demand from the existing level. The direction of national capacity expansion is given in the Thai power development plan 2010–2030, namely PDP2010 [8]. The same as most developing countries, the majority of electricity generation in Thailand is currently based on fossil energy, which account up to 88% of aggregated national electricity generation. Gas-fired power plants are the dominant part which generates about 68% while lignite- and coal-fired plants produce 11% and 8%, respectively. In spite of being highly dependent on natural gas, emission from the power sector is still a matter of great concern.

Twenty-five power plants, of which a power capacity of 100 MW or greater, including of the Electricity Generating Authority of Thailand (EGAT) and the independent power producers (IPPs) were selected in the study. The total installed capacities of the considered plants in the three-year studied period were 20,974, 22,382, and 23,743 MW, respectively, which accounted up to about 78% of the total national installed capacity (or 83% of total electricity generation). The analysis was classified by fuel types: coal, lignite, oil/gas, oil, diesel, and gas. Coal presented in the study commonly denotes the bituminous coal. Because of significant differences of the amount of emissions due to their abatement technology, the particulars of emission control equipment were taken into account. Table 1 presents the distribution of installed capacity and amount of annual electricity generation by types of fuel. The locations of the selected plants are also shown in Fig. 1.

The main criteria pollutants considered in the analysis comprised of sulfur dioxide (SO_2), nitrogen oxides (NO_X), and particulate matter (PM). The PM is a heterogeneous mixture which includes particles of various sizes. In general, fine PM is more destructive than coarse PM. Only PM with aerodynamic diameter less than 10 μm (PM_{10}), therefore, was chosen in the analysis.

Emission information was collected from several reference sources, i.e. environmental impact assessment (EIA) reports, EGAT's publication and reports, and also from the earlier studies. Table 2 summarizes the stack parameters of the considered emission sources. Most of existing plants were normally equipped with emission control system such as flue gas desulfurization (FGD) unit and electrostatic precipitator (ESP) in the oil-, coal- and lignite-fired plants, low-NO_X burner or water/steam injection in the gas-fired plants. However, these appeared to be lacking in the oil/gas- and some of oil-fired plants. Table 3 shows the aggregated average emission intensities. Obviously, the highest emission per unit of electricity generation was found in the power plants that lack appropriate abatement technology. The lignite- and coal-fired plants were the next two highest emission sources due to their lower quality fuels. In term of energy generation weighted average, the considered sources totally emitted 133, 192, and 8 ktons of SO_2, NO_X, and PM_{10} per annum, respectively. Almost half of SO_2 and NO_X emissions were contributed by the lignite-fired plants. And more than 40% of PM_{10} emission was caused by the oil/gas-fired plants. Moreover, the gas-fired plants also induced one third of total NO_X and PM_{10} emission figures.

3. Dispersion and modeling approach

To model the advection and transformation of the analyzed pollutants, the CALMET/CALPUFF modeling system was used. The dispersion results were shown as the increment at ground-level concentrations of the analyzed pollutants.

Table 1
Installed capacity and energy generations of the considered power plants.

Fuel type	Installed capacity (MW)			Energy generation (GWh)		
	2006	2007	2008	2006	2007	2008
All types	20,974	22,382	23,743	116,859	120,672	125,629
Coal	673	1347	1347	4024	10,218	10,801
Lignite	2400	2400	2400	18,044	18,518	18,691
Oil/gas (w/o FGD)	3230	3230	2920	13,265	11,390	10,236
Oil (w/o FGD)	400	400	0	1214	1224	0
Oil (with FGD)	340	340	340	1126	1015	202
Diesel	610	610	610	4	3	1
Gas	13,321	14,055	16,126	79,182	78,304	85,698

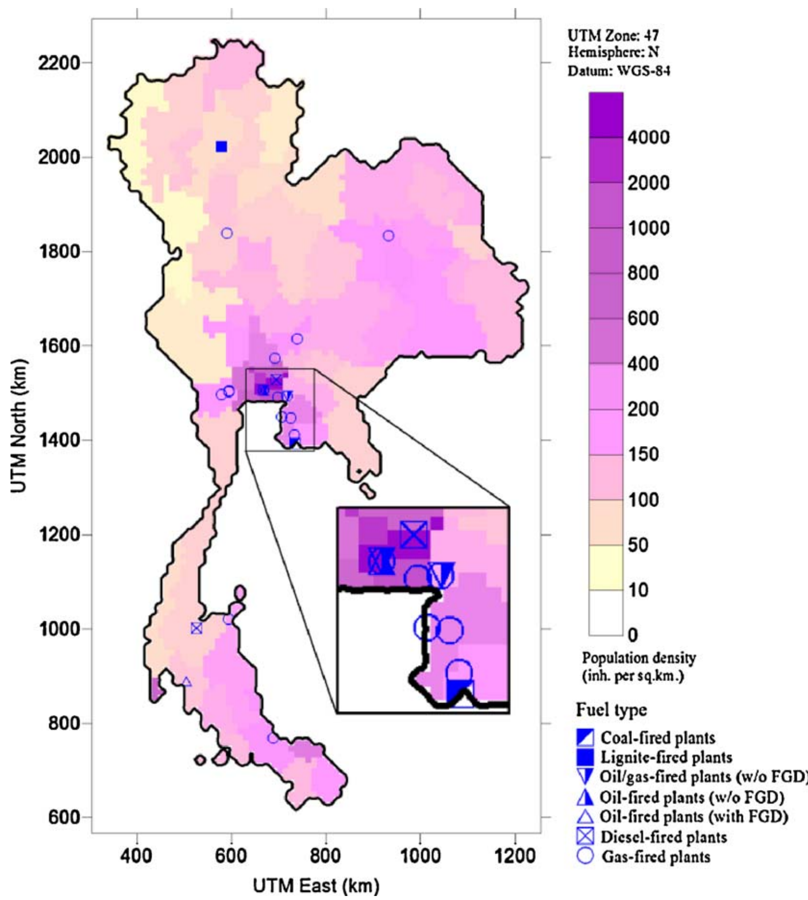

Fig. 1. Population density, locations of fossil power plants, and border of modeling domain.

3.1. CALMET/CALPUFF modeling system

The modeling system was adopted by the U.S. Environmental Protection Agency (U.S. EPA) as the preferred/recommended model for long-range transport in its "Guideline on Air Quality Models" [9]. The modeling system consists of three main components [10]: CALMET, CALPUFF, and CALPOST. CALMET is a diagnostic meteorological model that generates hourly wind and temperature fields on a three-dimensional gridded domain. CALPUFF is a multi-layer, multi-species, non-steady-state, Lagrangian Gaussian puff model which can simulate the impact of temporally and spatially meteorological variations on transport and transformation of the pollutants by using the prognostic meteorological data from the CALMET model. CALPOST is a post-processing program which

Table 2
Stack parameters of the considered power plants.

Fuel type	Number of stacks	Height (m)	Inner diameter (m)	Stack gas velocity (m s^{-1})	Temperature (K)
Coal	2	200	6.8	22.3	350
Lignite	10	150	5.8	19.0–25.6	352–377
Oil/gas (w/o FGD)	7	84–122	4.9–6.1	23.3–27.6	423–448
Oil (w/o FGD)	2	76	3.4	27.4	451
Oil (with FGD)	1	150	4.0	28.0	353
Diesel	4	32–34	5.5–6.4	31.5	805–826
Gas	71	11–150	2.4–7.2	12.5–50.0	366–805

Table 3
Average emission intensities (ton/GWh).

Fuel type	SO_2	PM_{10}	NO_X
All types	1.10	0.06	1.59
Coal	3.01	0.10	2.01
Lignite	3.43	0.04	4.74
Oil/gas (w/o FGD)	3.52	0.28	1.55
Oil (w/o FGD)	3.33	0.26	1.21
Oil (with FGD)	0.83	0.16	1.06
Diesel	1.64	0.04	1.63
Gas	0.01	0.03	0.85

processes the primary output of CALPUFF program to summarize the results of the simulation. In addition, the modeling system still comprised of a set of preprocessing programs to comply with the available meteorological and geophysical datasets.

Although the impacts could affect thousands of kilometers away from the sources, the receptors within boundary of Thailand were only considered in this study. The modeling domain covered 960 km by 1740 km area with grid spacing of 12 km. The 10 vertical layers were set at cell face heights of 0, 20, 40, 80, 160, 320, 640, 1200, 2000, 3000, and 4000 m above sea level. For primary input data, the meteorological information of twenty-four surface stations, two upper air stations, and five precipitation stations from Thai Meteorological Department (TMD) were used in order to develop the prognostic meteorological field by the CALMET and its preprocessing models. Terrain elevation data used in this study was generated from Shuttle Radar Topography Mission (SRTM) Version 2 with resolution of 3 arc-sec or approximately 90 m. And land-use data was taken from Global Land Cover Characterization (GLCC) Version 2 with resolution of 30 arc-sec or approximately 1 km.

To deal with chemical processes of the pollutants, the MESOPUFF II mechanism was selected in order to simplify the chemical conversion of SO_2 and NO_X which transformed to sulfate and nitrate aerosols, respectively. The hourly transformation rates were developed by a photochemical model. The daytime SO_2 oxidation was a function of background ozone concentration, solar radiation intensity, atmospheric stability index, and relative humidity. Similarly, the daytime NO_X oxidation was a function of background ozone concentration, solar radiation intensity, and plume NO_X concentration. For nighttime, the oxidations were assumed to be at constant rates of 0.2% and 2.0% for SO_2 and NO_X, respectively [11].

3.2. Dispersions of the criteria pollutants

The average seasonal surface wind pattern in Thailand is normally based on NE–SW–NE direction. Because of a relatively high proportion of calm wind (velocity less than 0.5 m s^{-1}), the primary PM and gaseous precursors were, therefore, dispersed in the vicinity of their emission sources. Hence, the pollutant concentrations near the sources became more significant. It should be noted that a number of large capacity power plants were located in the central area which was the most densely populated region of the country. Figs. 2–6 present the contour plots of annual average increments of the pollutants. It is clearly seen that the increments of SO_2 and NO_X concentrations could be divided into two significant areas (see Figs. 2 and 3). The highest concentration zone of the dispersion appeared to be around the lignite-fired plants which were located in the hilly north of Thailand. The lower concentration zone lay in the central area. Moreover, the central area was also noted to be the highest concentration zone of primary PM_{10} dispersion (see Fig. 4).

The secondary pollutants could disperse over a longer distance (see Figs. 5 and 6) than the primary PM_{10} and their gaseous precursors. The results showed that the secondary pollutants reached the significant values that could not be possibly negligible. Therefore, the total increment in PM_{10} shown in this analysis comprised of the primary PM_{10} and the secondary particulates (i.e. sulfate and nitrate aerosols). The mixture of those particulates in the dispersion results was commonly denoted as PM_{10}.

The modeling results gave the increments in annual population weighted average of 0.39 μg m^{-3} (min–max: 0–17.81 μg m^{-3}) for SO_2, 0.31 μg m^{-3} (0–22.88 μg m^{-3}) for NO_X, and 0.22 μg m^{-3} (0.01–1.69 μg m^{-3}) for PM_{10} concentrations. Although there have been a continuing increase in the total installed capacity and energy generation (see Table 1), the dispersion results of all considered pollutants tended to decrease in each subsequent year of the stud-

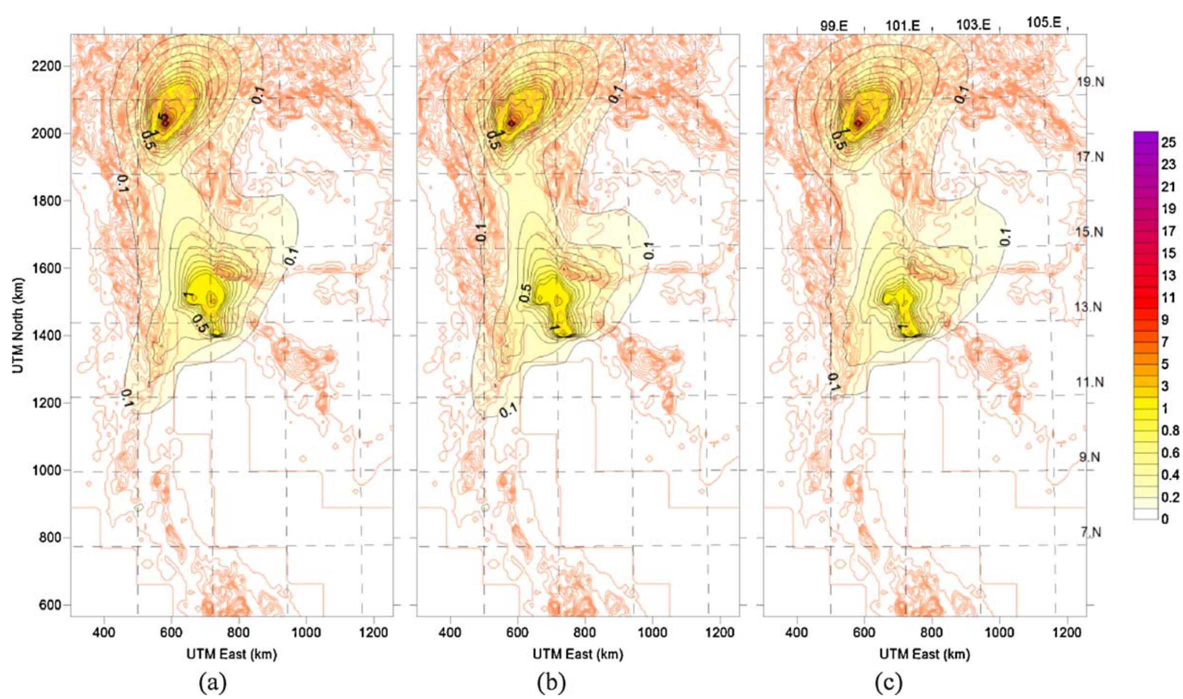

Fig. 2. Annual average concentration increments of SO_2. (a) 2006, (b) 2007 and (c) 2008.

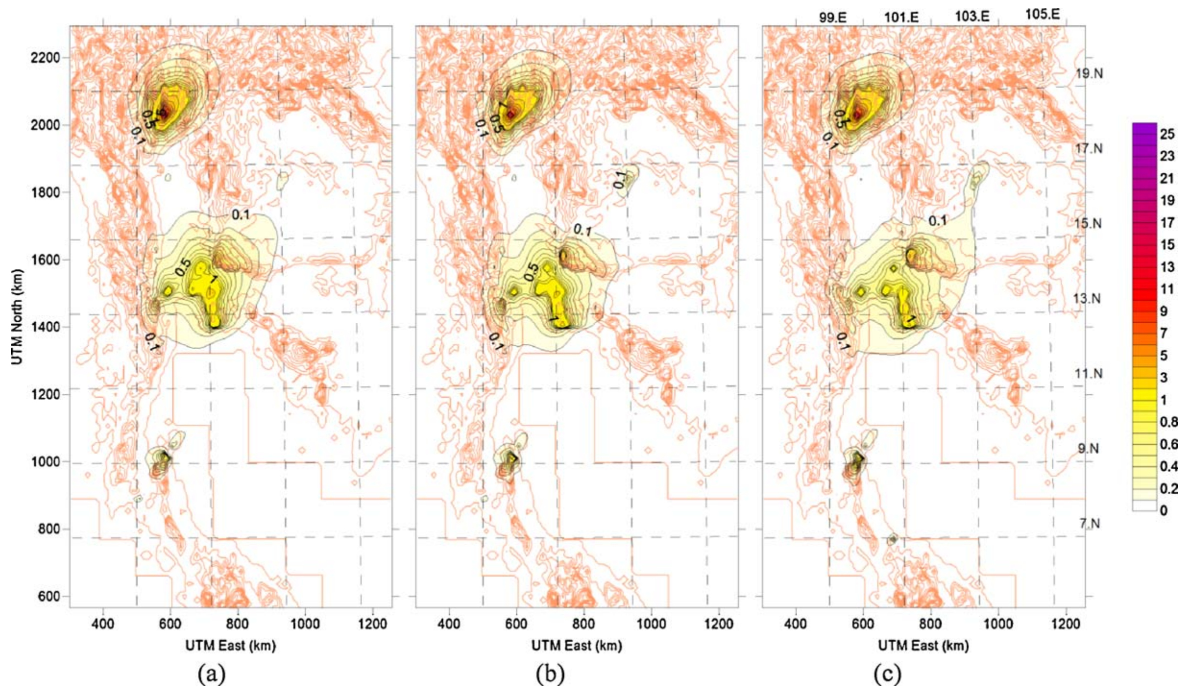

Fig. 3. Annual average concentration increments of NO_X. (a) 2006, (b) 2007 and (c) 2008.

ied period. Understandably, the fuel and technology improvements toward cleaner technology in the energy expansion plan were practiced. The significant change during the period was the replacements of old plants which lacked appropriate emission control equipment with new gas-fired plants.

4. Impact analysis

This section focused on the additional number of human health effects as the consequences of exposure to increment in the criteria pollutant concentrations. Public health degradations including premature mortality and morbidity were assessed in each grid receptor within the studied domain.

4.1. Selection of ERFs

A number of toxicological and epidemiological studies indicate significant relationship between the increment in airborne pollutant concentrations and adverse public health impacts [12–16]. Exposure to the criteria pollutants has been proved as a risk factor

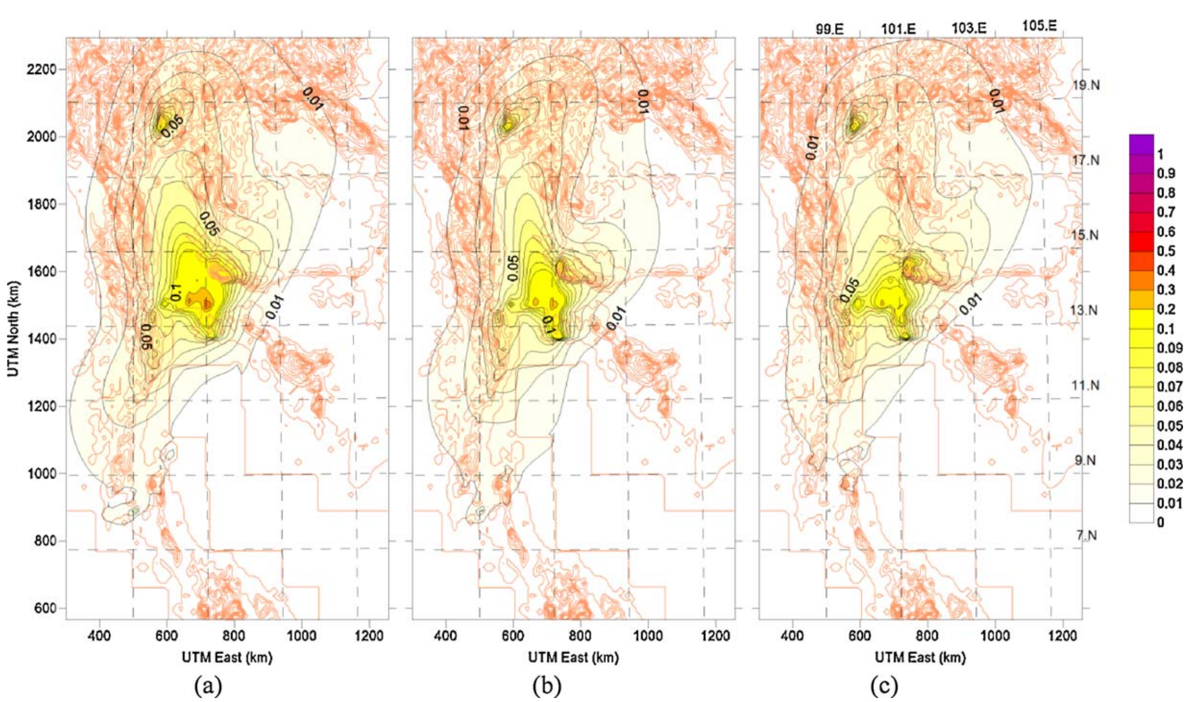

Fig. 4. Annual average concentration increments of primary PM_{10}. (a) 2006, (b) 2007 and (c) 2008.

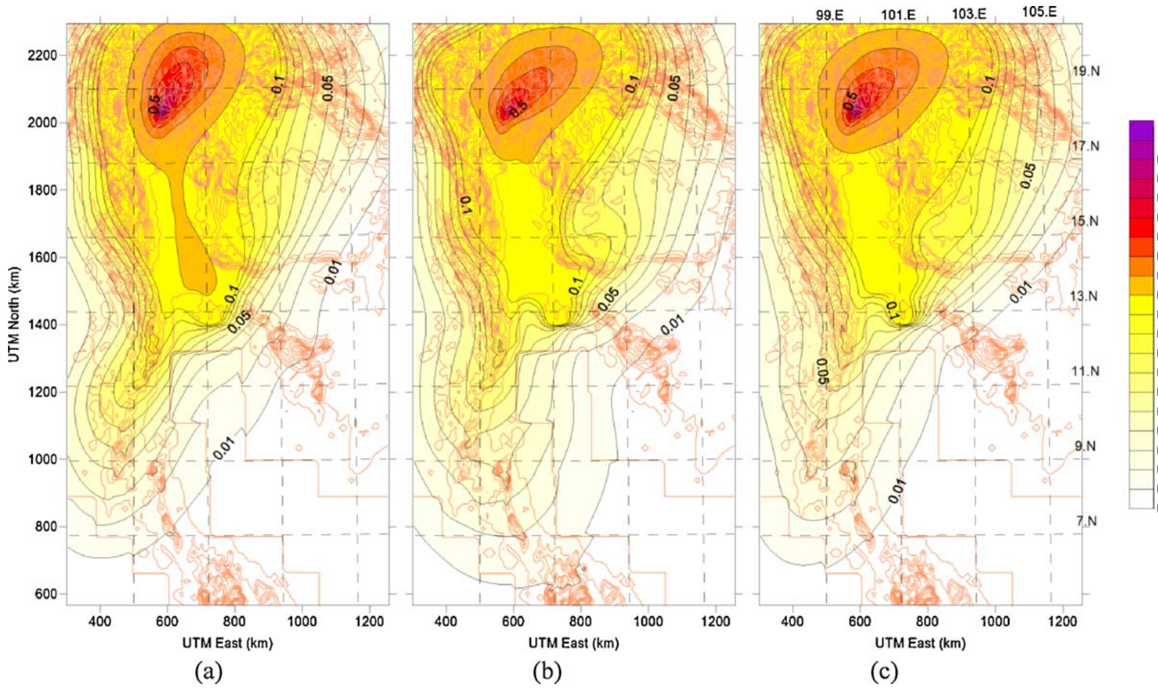

Fig. 5. Annual average concentration increments of sulfates. (a) 2006, (b) 2007 and (c) 2008.

for increasing human health impacts especially for related respiratory illnesses. The so-called exposure-response function (ERF) was used in order to define that relation. However, most epidemiological studies did not report the explicit ERFs. The studies usually showed in term of relative risk (RR). Therefore, key analytical procedure was to mapping the population data and baseline occurrences to air quality data from the dispersion results. In the analysis, the ERFs were assumed to be linear without threshold value. So, the expected cases could be calculated from the following equations:

$$\mathrm{ERF}(r, C(r, Q)) = \mathrm{SERF}(r) \times C(r, Q) \qquad (1)$$

$$\mathrm{SERF} = \mathrm{IRR} \times \text{Baseline rate} \times F_{POP} \qquad (2)$$

where $C(r,Q)$ represented the average incremental change in ground-level concentration ($\mu g\,m^{-3}$) at position of vector r and emission rate Q. The slope of ERF, SERF, was calculated from Eq. (2). IRR stood for the increment of relative risk (percent/$\mu g\,m^{-3}$) which represented the excess risk of health impacts resulting from incremental change in pollutant concentrations. Baseline rate was the nominal rate of occurrence of the considered diseases. F_{POP} denoted the fraction of population at risk normally based on age-specific groups.

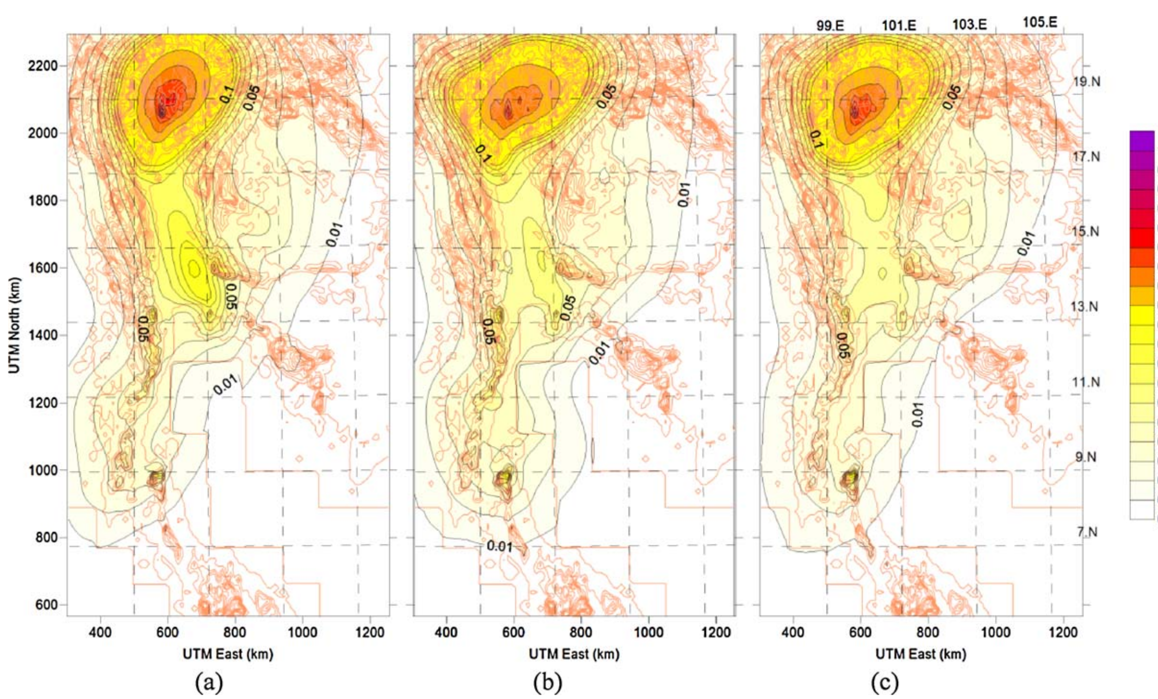

Fig. 6. Annual average concentration increments of nitrates. (a) 2006, (b) 2007 and (c) 2008.

Table 4
Summary of incident rates used in this study.

Health endpoint	Pollutant species	F_{POP}[a] (%)	Incident rate (cases/person year $\mu g\, m^{-3}$)		
			Central	Low	High
Premature mortality	PM_{10}	100	6.882E−06	4.515E−06	9.304E−06
	SO_2	100	8.864E−06	4.404E−07	1.740E−05
Morbidity					
CB in adults (≥25 years)	PM_{10}	63.7	1.411E−05	1.296E−06	2.794E−05
RHA	PM_{10}	100	4.543E−05	2.271E−05	6.814E−05
	SO_2	100	1.262E−05	NQ[b]	2.271E−05
	NO_X as NO_2	100	NQ[b]	NQ[b]	2.019E−05
CHA	PM_{10}	100	4.717E−05	2.621E−05	6.814E−05
ERV	PM_{10}	100	4.112E−05	1.121E−05	7.476E−05
AB in children (<25 years)	PM_{10}	36.3	4.406E−05	1.944E−05	7.229E−05
ASA in children (<15 years)	PM_{10}	21	5.984E−04	3.672E−04	8.432E−04
ASA in adults (≥15 years)	PM_{10}	79	8.742E−05	4.259E−05	1.323E−04
RAD in adults (≥18 years)	PM_{10}	74.3	5.800E−02	2.900E−02	9.100E−02
ARS	PM_{10}	100	3.000E−01	2.200E−01	7.400E−01

[a] Fraction of population at risk based on 2007 population census of Thailand.
[b] NQ = not quantify.

The selection of ERFs relied on available published literatures. Although, numerous studies carried out in developed countries indicate highly corresponding results of association between pollutants, especially for PM, and their adverse health impacts, the different excess risks shown in the studies for different areas might be attributed to, for example, the disparities of chemical composition of the analyzed pollutants, population characteristics, background health status, and local meteorological conditions [17]. In order to determine the appropriate ERFs, the epidemiological studies in Thailand were preferred and used in this study. The rest of the required data were carefully reviewed from other studies.

The available studies on ERFs of premature mortality in Thailand were traced back to late 1990s. Ostro [18] indicated that, in Bangkok, 10 $\mu g\, m^{-3}$ increasing in PM_{10} was associated with a 1–2% increase in all natural mortality, 1–2% increase in cardiovascular mortality, and 3–6% increase in respiratory mortality. More recent study, Vichit-Vadakan et al. [17] using five-year time-series analysis, found that the excess risk for all natural mortality was 1.3% [95% confidence interval (CI): 0.8–1.7] per 10 $\mu g\, m^{-3}$ increase in PM_{10} concentration which agreed well with the previous study. In addition, Wong et al. [19] further estimated the amount of excess risk of 1.61% (95%CI: 0.08–3.16) corresponding to 10 $\mu g\, m^{-3}$ increase in SO_2 concentration. In the paper, only the latest available studies were selected. Although there were some studies giving the relation between NO_X and mortality impact, the evidences were not strong enough to represent the explicit relation. This impact, therefore, was not included in this study.

Moreover, the pertinent studies indicated that increments in the criteria pollutant concentrations also produce additional risk of various types of illnesses, for example, an increasing in number of hospital admissions and prevalence of relevant respiratory diseases and symptoms. In summary, nine health endpoints of morbidity were considered in this analysis:

- Chronic bronchitis (CB) in adults
- Respiratory hospital admissions (RHA)
- Cardiovascular hospital admissions (CHA)
- Emergency room visits (ERV)
- Acute bronchitis (AB) in children
- Asthma attacks (ASA) in children
- Asthma attacks (ASA) in adults
- Restricted activity days (RAD) in adults
- Days with acute respiratory symptoms (ARS)

Due to limitations of epidemiological studies in Thailand, evidences of the ERFs used in this study included revision of data from other several sources [12,13,20–24].

4.2. Population data and baseline occurrences

The population data employed in this study was based on 2007 population census conducted by the Department of Provincial Administration, Ministry of Interior (DOPA). There were 63 million inhabitants on 513,120 km^2 area. The data was used to define the number of population and the distribution in each grid. The population densities were assumed to be constant at provincial level. The data was also classified by age-specific differences depending on the reference studies.

Mortality statistics in 2007 were carried out from the Bureau of Policy and Strategy, Ministry of Public Health. The data were categorized according to the International Classification of Diseases, 10th revision (ICD-10). In this study, A00-R99 codes were chosen for all natural mortality. The baseline mortality rates were then defined in each grid. In the studied domain, the baseline mortality rates ranged from 0.003618 to 0.008444 per person-year and were averaged for 0.005558 per person-year countrywide.

In order to determine the baseline rates of morbidity, hospital admission statistics were collected by health service facilities of the Ministry of Public Health. The data were categorized into two main groups, i.e. respiratory and cardiovascular diseases. As the statistics previously mentioned were from governmental health services, the baseline rates were extrapolated to include private health services/hospitals, with assumption that the available data accounted for 70% (according to the proportion of number of hospital beds) of total occurrences. In similar to the baseline mortality rate, the baseline occurrences of RHA and CHA were also set in each grid which established the overall average of 0.016125, 0.017891 cases per person-year, respectively. For the baseline rates of other morbidities, treatment numbers of the illness records in health service facilities were unclear. The prevalence of asthmatic subjects was referred to Dejsomritrutai et al. [25] who made a sample study of population covering all regions of the country. In case of bronchitis, the prevalence was evaluated by World Health Organization. And other minor respiratory symptoms (i.e. RADs and ARSs) were suggested by Chestnut et al. [22] which studied the impact of PM_{10} for Bangkok population.

Referring to the above literatures, after IRRs multiplied by baseline rates which were defined in term of "cases per person-year", the products were taken as incident rates, which are summarized in Table 4. According to Eqs. (1) and (2), the expected cases were calculated by multiplying the incident rate with incremental change in the pollutant concentration and fraction of population at risk.

Table 5
Central estimation of annual average of human health impact (cases/year).

Health endpoint	All types	Coal with FGD	Lignite with FGD	Oil/gas w/o FGD	Oil		Diesel	Gas
					w/o FGD	With FGD		
Premature mortality	354	66	80	177	31	1	0[a]	21
Morbidity								
CB in adults	128	23	32	49	6	0[a]	0[a]	24
RHA	1249	186	311	436	68	3	0[a]	297
CHA	731	121	202	270	36	2	0[a]	133
ERV	586	104	146	224	28	2	0[a]	109
AB in children	228	40	57	87	11	1	0[a]	42
ASA in children	1790	317	446	684	86	5	0[a]	333
ASA in adults	983	174	245	376	47	3	0[a]	183
RAD in adults	613,593	108,552	152,873	234,434	29,509	1743	22	114,067
ARS	4,272,118	755,793	1,064,376	1,632,238	205,454	12,137	157	794,189

[a] Less than 0.5 cases/year.

4.3. Marginal health damages

The estimation of human health impacts resulting from the increments in the pollutant concentrations is presented in Table 5. Emissions from all considered sources appear to potentially cause approximately 354 deaths annually (95%CI: 82–630 deaths). In case of morbidity, they provided the increment of almost 2000 cases per year in hospital admissions which could be clarified as 63% of respiratory diseases and 37% of related cardiovascular symptoms. They also indicated the annual additional occurrences of 128 cases of CBs, 586 ERVs, 228 ABs, 2773 ASAs, 0.6 million RADs, and 4.3 million ARSs.

The largest share of health impacts appears to be associated with the oil/gas-fired plants. A half of the total mortality and more than one third of all health endpoints of morbidity impacts were caused by the oil/gas-fired plants. The second largest impact was contributed by the lignite-fired plants which caused a quarter of total mortality and morbidity. The coal-fired plants came next with almost 20% of all impact. The next two significant impacts were from the oil-fired plants without FGD and the gas-fired plants which caused 9% and 6% of total mortality and also brought 5% and almost 20% of total morbidity, respectively. The oil-fired plant with FGD and the diesel-fired plants were the last ones with the relatively low impact among the other fuel types.

5. External costs

The monetary valuation is a conventional method for aggregating several impacts of different physical units into a single estimation [26]. The economic values of health impacts, or the so-called health damage costs, were evaluated to reflect the external costs of electricity generation. Owing to intangible aspects of the health impact valuations, the economic values could not be directly estimated. In general, willingness-to-pay (WTP) and costs of illness (COI) are the two main categories used to evaluate the costs of health degradation [27]. The WTP is an individual preference for avoiding or reducing the risk of death or illness [21]. The COI is comprised of, for example, health service expenditure, and lost wages or missing of income during illness. The value of statistical life (VSL) is another way of stating the mortality valuation which is normally based on WTP.

In case that the national studies of monetary valuation could not be found in the literature, benefit transfer was the most useful method to apply the available results from the studies of developed countries which could be calculated as follows:

$$U_{V\,(Thailand)} = U_{V\,(\text{Reference country})} \times \left(\frac{\text{PPP}_{\text{Thailand}}}{\text{PPP}_{\text{Reference country}}}\right)^{\gamma} \quad (3)$$

Table 6
Unitary costs of health impact.

Health endpoint	Cost per case (2005 US$)	Type of estimation
Premature mortality	1,582,226.62	VSL/WTP
Morbidity		
CB in adults	69,548.74	WTP
RHA	3843.99	COI
CHA	4118.56	COI
ERV	142.78	COI
AB in children	90.61	COI
ASA	10.07	WTP
RAD in adults	17.02	WTP/COI
ARS	3.20	WTP

where PPP was the gross national income (GNI) per capita adjusted for purchasing power parity. And γ represented the income elasticity.

In order to determine the valuation of mortality in Thailand, the VSL from a contingent valuation survey conducted in Bangkok by Vassanadumrongdee and Matsuoka [28] gave good agreement with the study of Voorhees et al. [29] which recommended the value for Bangkok area using benefit transfer method. In this analysis, the VSL obtained by the previous study [28] was chosen because of their original survey. Due to a dearth of the morbidity valuing studies in developing countries, the unitary values (U_V) in the analysis were mainly referred to the US studies [16] in order to determine the morbidity values for Thailand. From Eq. (3), Thai and US PPP were equal to 7490 and 46,220 US$ in 2007, respectively [30], while γ was assumed to be 1.0, giving the benefit transfer ratio of 0.1621. Based on these assumptions, the unitary cost estimations of mortality and morbidity are presented in Table 6. It was also noted that all monetary values in the analysis were converted to 2005 US$.

The energy generation weighted average of total health damage costs and costs per kWh of electricity generation are shown in Table 7. The results showed that the gross national health damage cost was approximately 600 million 2005 US$ annually (low-high: 152–1076 million US$). The aggregated average unitary cost was 0.50 US$ cent kWh^{-1} ranging between 0.05 and 4.17 US$ cent kWh^{-1} by fuel types. The oil-fired plants without FGD showed the highest unitary cost which was more than eight times comparing with the overall average. The oil/gas-fired plants which induced the most influence of health impacts contributed almost half of total damage costs and also led to the second highest cost per kWh. Although most of the emission intensities of the lignite-fired plants were higher than that of the coal-fired plants (see Table 3), the average cost per kWh was considerably low. It was mainly because the lignite-fired plants were located in remote areas with low population density around the power plants. Gas was considered as the cleanest fuel among commercial fossil fuel. The gas-fired plants which were scattered around the country generate almost 70% of

Table 7
Aggregated average of health damage cost.

Fuel type	Annual cost (million US$/year)			Unitary cost (US$ cent kWh^{-1})		
	Central	Low	High	Central	Low	High
All types	601.28	151.71	1075.75	0.4982	0.1257	0.8913
Coal	111.72	26.11	201.82	1.2180	0.2868	2.1985
Lignite	136.41	40.26	238.54	0.7407	0.2185	1.2952
Oil/gas (w/o FGD)	295.48	59.68	541.77	2.4864	0.4990	4.5616
Oil (w/o FGD)	50.83	8.28	94.90	4.1714	0.6796	7.7877
Oil (with FGD)	1.09	0.35	1.90	0.1098	0.0351	0.1908
Diesel	0.04	0.01	0.07	0.9916	0.1709	1.8435
Gas	40.96	24.08	61.44	0.0506	0.0298	0.0759

Table 8
Distribution of central estimation of health damage cost.

Fuel type	By types of impact (%)		By species of emitted pollutant (%)		
	Mortality	Morbidity	SO_2	Primary PM_{10}	NO_X
All types	93	7	83	8	9
Coal	94	6	92	3	5
Lignite	92	8	82	1	17
Oil/gas (w/o FGD)	95	5	90	8	2
Oil (w/o FGD)	96	4	92	7	1
Oil (with FGD)	89	11	75	16	9
Diesel	96	4	96	1	3
Gas	81	19	10	40	50

the gross national electricity generation, but, contributed only 7% of the total damage cost. As a result, they yielded the lowest cost per kWh comparing with the other fuel types.

The mortality costs were the crucial part of the health damage costs, accounted up to 93% of the total costs (ranging between 81% and 96% by fuel types). Nevertheless, costs due to morbidity impacts were still important. One third of the total morbidity cost was taken from valuing impact of ARSs. For the next prominent health endpoints, RADs, CBs, and hospital admissions caused 25%, 22% and 19% of the morbidity cost, respectively. In this case, the values of ERVs, ABs in children, and ASAs could be negligible. Considering the cost distribution by species of emitted pollutants, the major impact for all considered sources was induced by SO_2 which accounted up to 83% of the total costs while the costs from NO_X and primary PM_{10} contributed only 9% and 8%, respectively. The distribution of health damage costs by types of impact and by pollutant species are presented in Table 8. The cost distributions of each fuel type gave a similarly pattern; the gas-fired plants, however, were exception. Although, the mortality cost was still the major damage cost of the gas-fired plants, it contributed the lowest proportion which was different from that of other fuel types. For obvious disparity, NO_X was the largest problem of the gas-fired plants which contributed a half of their total damage cost. In addition, primary PM_{10} also posed another important problem with 40% of the total cost.

While the cost per kWh is highly site-specific, the cost per ton of emitted pollutants is of more general unit which takes the power plant location into account but is not dependent on quality of fuel used and emission abatement equipment. Table 9 summarizes the specific cost per ton of the emitted pollutants. The first two highest specific costs per ton were both still contributed by the oil/gas- and oil-fired plants without FGD, whereas the lignite- and oil-fired plants with FGD which were located in remote area tended to have the lowest cost per ton of the emitted pollutants.

Comparing to other studies, Thanh and Lefevre [31] assessed the health impact of electricity generation in Thailand. The results indicated that the cost by fuel types were from 0.006 to 0.05 US$ cent kWh^{-1}. The results in the recent study provided much higher values than the previous study. This was probably due to different assumptions made by authors. In Thanh and Lefevre's [31] study,

Table 9
Specific health damage cost per ton of emitted pollutants (US$/ton).

Fuel type	SO_2	Primary PM_{10}	NO_X
All types	3767	5883	286
Coal	3718	3964	296
Lignite	1775	2084	259
Oil/gas (w/o FGD)	6379	6637	348
Oil (w/o FGD)	11,463	11,773	403
Oil (with FGD)	994	1058	98
Diesel	5832	2316	163
Gas	5438	6405	302

two species of criteria pollutants i.e. PM_{10} and sulfate aerosols were investigated, with objective to estimate the damage costs of health impacts of mortality and three health endpoints morbidity. Only one unit of selected power plants was chosen to be representative for each fuel type. The value of mortality impact which was evaluated from the transfer method in previous study was less than the national study used in the recent study.

For the Syrian case, the health damage costs of Syrian electricity generation studied by Hainoun et al. [26] were estimated at 0.06, 1.96, and 2.53 US$ cent kWh^{-1} for the gas-, oil/gas-, and oil-fired plants, respectively. The result of the gas-fired plants was comparable to the Thai case in recent study. But the results of the oil/gas- and oil-fired plants were lower in spite of having 3–5 times higher SO_2 emission intensity. It was possibly caused by lower population density in the vicinity of the power plants and the ERFs used in the analysis. Nevertheless, it should be emphasized that the valuation was based on individual preferences. Therefore, the difference in estimated values may vary from country to country depending on the economic disparity.

6. Conclusions

The IPA is a useful method to evaluate the external costs of electricity generation. The principal factors affecting these results were mainly associated with geophysical locations, distribution of population density, meteorological conditions, quality of fuel used, and emission abatement technologies. Although all emissions of the considered plants comply with the national emission

standards, they still imposed significant impact on human health degradations. The results showed that the annual average cost of public health damage resulting from Thai fossil electricity generation in 2006–2008 was approximately 600 million 2005 US$ which accounted to 0.3% of Thai GDP at that time. Aggregated average of the cost per kWh of generated electricity was 0.50 US$ cent kWh^{-1}. The highest damage cost indicators were caused by the power plants without emission control equipment. These findings underline the necessity of appropriate emission abatement technologies especially for the power plants that are located in the vicinity of the most densely populated region. According to the distribution of the results, mortality was the crucial type of human health impact which accounted for 93% of the total damage costs. However, morbidity was still significant. There were 5 of 9 health endpoints considered in the analysis significantly influencing the morbidity cost. For other point of view, SO_2 caused 83% of the overall damage cost which was the largest problem of the airborne pollutants emitted from power plants.

In order to take the disparity between countries into account, the current study included the available national studies and country-based information in the analysis. However, some of the results presented here still contained a number of uncertainties. Approximating the meteorological and epidemiological data was required for the missing observations. All impacts were merely calculated on population within territorial boundary of Thailand and did not take the effects of trans-boundary into account. It is worth pointing out that the ERFs seemed to be the most significant uncertainty in the analysis. Further development of epidemiological research and health service information system in the country would help clarify this uncertainty. In spite of the existence of these uncertainties, the application of these results is still useful for policy maker. The specific results from the bottom-up framework potentially provide more information in policy decision processes. In public burden perspective, move toward cleaner energy structure is required in order to reduce both aggregate and unitary external costs. For wider purpose, full assessment of externality including climate change and other non-health impacts should be quantified.

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